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MEMORANDUM REPORT ARBRL-MR-03097

ARMOR-PENETRATOR PERFORMANCE MEASURES

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March 1981

US ARMY ARMAMENT RESEARCH AND DEVELOPMENT COMMAND
BALLISTIC RESEARCH LABORATORY
ABERDEEN PROVING GROUND, MARYLAND

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REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER MEMORANDUM REPORT ARBRL-MR-03097	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) ARMOR-PENETRATOR PERFORMANCE MEASURES		5. TYPE OF REPORT & PERIOD COVERED Final 6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Konrad Frank		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS US Army Ballistic Research Laboratory ATTN: DRDAR-BLT Aberdeen Proving Ground, MD 21005		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS RDT&E 1L162618AH80
11. CONTROLLING OFFICE NAME AND ADDRESS US Army Armament Research and Development Command US Army Ballistic Research Laboratory ATTN: DRDAR-BL Aberdeen Proving Ground, MD 21005		12. REPORT DATE MARCH 1981 13. NUMBER OF PAGES 30
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Distribution limited to US Government agencies only; Test and Evaluation; Mar 1981. Other requests for this document must be referred to Director, US Army Ballistic Research Laboratory, ATTN: DRDAR-TSB, Aberdeen Proving Ground, MD 21005.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

space effectiveness
mass effectiveness
thickness equivalence
relative thickness
relative areal mass
armor quality factor
apparent density
residual penetration

20. ABSTRACT (Continue on reverse side if necessary and identify by block number) (lrs)

A review is presented of armor effectiveness measures as used in ballistics. Emphasis is placed on the fact that simple effectiveness measures attempt to describe a complex armor-penetrator interaction by a single number. Procedures for ballistic testing designed to derive meaningful measures are discussed.

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1 INTRODUCTION

The performance of armors and armor penetrators is often described in comparative terms: x inches of steel gives the same protection as y feet of wet clay; bullet A perforates a steel helmet at 600 yards, bullet B can do it only out to 50 yards; 3/4 inches of special treated steel gives the same ballistic protection as 1¼ inches of mild steel. Such relative performance measures are useful for comparing armors (complete armor packages) or armor materials (elements of an armor package) as to their ability or merit to defeat various armor penetrators (eg CE, KE). Conversely, analogous measures can be used to compare the capabilities of various armor penetrators to defeat (perforate) armors. These relative performance measures are derived from the ballistic evaluation of armor packages or armor elements (materials) against some particular penetrator. Therefore, the relative measures will reflect the intrinsic properties of both the armors and the penetrators. Some of the measures used in the past (References 1 and 2) are discussed below.

The relative areal mass, ε_m, a nondimensional index, expresses the areal mass of a given target in terms of the areal mass of an all-steel reference target of equal ballistic protection. The reference target is usually rolled homogeneous armor (RHA).

The thickness equivalence, e_i, is usually applied to evaluate or describe the performance of an element of thickness T_i contained within a composite target. If steel of thickness T_{si} in place of the element T_i results in the same overall response of the target to penetrator attack, e_i is given by the ratio of T_{si} to T_i.

The relative thickness, ε_s, is derived by applying the thickness equivalence concept to the complete armor package. It expresses the thickness of the armor as a nondimensional ratio of an all-steel target having the same ballistic protection.

Other measures less frequently used are "reduction factors" (derived from the difference in residual penetrations between two targets for otherwise identical test conditions) and "apparent" or "effective" density (Reference 1). All these measures, and the space and mass effectiveness factors to be discussed below, are interrelated: They express in simple form merit or penalty indices when comparing

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[1] *Allison, F.E., "Defeat of Shaped Charge Weapons," Final Report, Carnegie Institute of Technology, April 1960 (AD 316551).*
[2] *Kronman, S., Bock, V., and Caudill G., "Stopping Power of Sand Against Shaped Charge Jets," BRL TN 1246, February 1959.* (AD #378704)

unconventional or composite armors to equal performance all-steel armors. By convention, the common base line against which armors and penetrators are measured is always rolled homogeneous armor (RHA). Applied correctly the simple indices serve a useful purpose. However, because of the simplicity, many of the underlying complications tend to be ignored, and frequently the indices are misused. It is advisable to keep in mind that the magnitude of the indices depends critically on many details of the armor and the penetrator, and their interaction during the penetration/perforation process. To paraphrase from Reference 1: "The simplest measure of protection afforded by a given armor design is the total target thickness penetrated. Since it is obvious that the total penetration has no meaning unless the complete details of both the penetrator and the armor are specified, little difficulty is encountered in using this measure." Following the above recommendations would be the preferrable procedure in cataloging or comparing the performance of armor packages, armor materials, and armor penetrators. Nevertheless, for many purposes, simpler measures reduced preferrably to one number, are adequate provided this single number is properly derived and properly applied.

2 ARMOR EFFECTIVENESS MEASURES, E_s AND E_m

Recently a multi-national working group agreed on using armor performance measures expressed in terms of space- and mass-effectiveness factors, E_s and E_m. These are defined by

$$E_s = T_o/T \quad = \text{thickness of RHA/thickness of armor,}$$

$$E_m = \rho_o T_o/\rho T = \text{areal mass of RHA/areal mass of armor.} \tag{1}$$

T_o and ρ_o are the thickness and density of the reference armor steel target (RHA) that "just defeats" a given penetrator, while T and ρ are the thickness and density of the armor package to be evaluated, which likewise "just defeats" the same penetrator. Identical attack parameters (eg, stand-off for CE, striking velocity for KE) are implied. For targets at obliquity T and T_o are taken as line-of-sight quantities in the direction of penetrator attack. The condition that the armor "just defeats" the penetrator, or vice-versa, is the idealized matched case which is difficult to obtain in practice. Usually, a fixed armor package (ρ, T) is constructed and then subjected to ballistic testing with several penetrators.

With KE penetrators it is possible to determine the "limit velocity" for the target, and then, knowing the perforation capability T_o of the KE penetrator at the same velocity, the E_m and E_s factors can be computed. These numbers apply in the strict sense of the definitions only for that particular KE penetrator striking the target (armor package) at that particular velocity.

Establishing the ideal matched condition with CE penetrators is more difficult. In general, scaling of the armor package or scaling of the CE warhead would be required. Therefore, most of

the time the armor effectiveness measures are derived from mismatched ballistic experiments. Nevertheless, it is instructive to examine the ideal matched case, rarely found in practice, in some detail before proceeding to the general, mismatched situation.

2.1 Ideal matched case

For this special case, the target effectiveness measures are well defined. Rearranging the definitions in (1),

$$E_s T \equiv T_o, \text{ and}$$

$$E_m \rho T \equiv \rho_o T_o,$$

it becomes obvious that this is a process of comparing the thickness, T, and the areal density, ρT, to corresponding numbers of the homogeneous reference material (RHA, subscript 0) which produces the same ballistic result: Penetrator and target just defeated. Since the ballistic test is in fact comparing the well defined response of an armor package to the same kind of response in RHA, $E_s T$ and $E_m \rho T$ may be interpreted as the effective RHA thickness and RHA areal density of the armor. The ratio of E_s and E_m is simply the relative density of the complete armor package, ρ/ρ_o, which is known prior to any ballistic test. It is therefore reasonable to associate the product of E_s and E_m with the ballistic "quality" of the armor:

$$\begin{aligned} E_s/E_m &= \rho/\rho_o = r^2 \\ E_s E_m &\equiv Q^2 \end{aligned} \qquad (2)$$

In terms of Q and r the space and mass effectiveness factors of the armor are:

$$\begin{aligned} E_s &= rQ = 1/\varepsilon_s, \\ E_m &= Q/r = 1/\varepsilon_m, \end{aligned} \qquad (3)$$

where the relation to the relative thickness, ε_s, and the relative mass, ε_m, is also included. The choice of r and Q is especially suitable for describing the response of homogeneous or quasi-homogeneous targets to idealized shaped charge penetrators: Q equal to one is simply the "density law" (penetrations in two different homogeneous materials are inversely proportional to the square root of their density ratio), while $Q \neq 1$ signifies "abnormal" stopping power of the material, or as used here, of the complete armor package. Armors with Q-factors greater than 1 are both thinner and lighter than armors of the same

density having a "normal" response to penetrator attack, provided both are designed to just defeat the same penetrator. The apparent or effective density of the armor, ρ_e, a concept rarely used today, is related to the Q-factor by:

$$\rho_e = \rho Q^2. \tag{4}$$

The discussions above and the relations among the various quantities can be summed up as follows. The effectiveness factors, E_s and E_m, are well defined in the ideal matched case (..just defeated..). The two factors are not independent. Both depend on a quantity determined by the details of the armor (r^2, the ratio of the real, average density of the armor to that of RHA), and a second quantity derived from a ballistic evaluation (Q, the quality of the armor). There is no reason to expect that the Q of a given armor will have the same value for different penetrators. Therefore, for a given armor package, both E_s and E_m are expected to depend on the penetrator used to evaluate the armor. On the other hand, their ratio depends only on the details of the armor and it is known a priori. These simple concepts are applied to a complete armor package.

Some of the underlying complications and implicit assumptions are revealed by examining a multi-element array, or multi-layer, multi-material laminated armor containing n sequential elements of thickness T_n and density ρ_n. The thickness and areal density of the armor are given simply by:

$$\begin{aligned} T &= T_1 + T_2 + \dots + T_n, \\ \rho T &= \rho_1 T_1 + \rho_2 T_2 + \dots \rho_n T_n. \end{aligned} \tag{5}$$

The matched ballistic evaluation of this armor and the resulting comparison of ballistic performance to RHA is represented by:

$$\begin{aligned} T_o &\equiv E_s T = e_1 T_1 + e_2 T_2 + \dots e_n T_n, \\ \rho_o T_o &\equiv E_m \rho T = m_1 \rho_1 T_1 + m_2 \rho_2 T_2 + \dots m_n \rho_n T_n. \end{aligned} \tag{6}$$

e_i is the RHA thickness equivalence of the individual elements, and, by similar reasoning, m_i their RHA mass equivalence. Using the relation $E_s/E_m = \rho/\rho_o$ it follows that $m_i = e_i \rho_o/\rho_i$ so that the second line of (6), as expected, yields no new information. As shown earlier, one quantity (in this case E_s) suffices to describe the ballistic response

of the armor. The other quantities of interest (E_m, Q, ρ_e) are determined from the first one by using the known details of the armor (ρ_i, T_i, r^2). The RHA thickness equivalence (e_i) of the individual target elements or layers is in general not easy to quantify separately. It represents the ballistic response of an individual element, and, its interactions with the neighboring elements. Therefore, e_i depends not only on the intrinsic properties of the i-th element, but also on the particular environment provided for that element in a particular armor package. The overall response of the armor, expressed as effective or equivalent RHA thickness, E_sT, is determined by individual and cooperative contributions from all target elements. It is therefore not surprising that armor effectiveness measures (E_s, E_m, or Q) are in general highly dependent on the details of the armor and the details of the penetrator.

2.2 Mismatched case

As pointed out earlier, it is in general either too difficult or too costly to establish the conditions necessary for a well matched ballistic test with the armor just defeating the penetrator, or vice versa. In the overmatched case, the penetrator perforates the armor and produces additional residual penetration in an RHA witness pack placed behind the armor. The performance of the same penetrator into RHA under identical attack conditions (eg, stand-off for CE, striking velocity for KE) is known (T_o, P_o). Ignoring the differences between penetration and perforation*, and invoking the concept of equivalent RHA thickness, the following approximate relations* hold:

$$E_sT + R_o = T_o,$$
$$E_m\rho T + \rho_oR_o = \rho_oT_o, \tag{7}$$

where R_o is the residual penetration into the RHA witness pack. From (7), the required measures can be computed as follows:

$$E_s = (T_o - R_o)/T,$$
$$E_m = \rho_o(T_o - R_o)/\rho T = E_s/r^2, \tag{8}$$
$$Q = E_s/r.$$

The differences between penetration and perforation and the implications of using (7) are addressed in Appendices A and B.

In the undermatched case, the penetrator does not perforate the target but penetrates only to some distance from the back face of the target. If the last target element is RHA, and if this element is partially perforated, and ignoring again the differences between penetration and perforation, the same formal procedures apply. This is justified by applying the equivalent RHA thickness concept and noting that:

$$T_o \equiv e_1T_1 + e_2T_2 + \dots e_{n-1}T_{n-1} + e_n\,(T_n - R_n),$$

where R_n, the perforation margin, is measured from the back face of the armor to the point where the penetration ceased. Because the last target element, n, is RHA, it is reasonable to assume $e_n = 1$ and R_n may be designated as R_o and interpreted as negative residual penetration into RHA. Since

$$E_sT = e_1T_1 + e_2T_2 + \dots e_nT_n,$$

the relations

$$E_sT - |R_o| = T_o,$$

$$E_m\rho T - \rho_o|R_o| = \rho_oT_o$$

follow so that equation (8) can be used, provided R_o is taken with the proper sign. In either case, overmatch or undermatch, R_o, is the residual penetration into RHA, measured from the back face of the armor: Positive into the RHA witness pack, and negative into the last RHA element of the armor.

In the case of severe undermatch a significant portion of the armor does not take part in the armor-penetrator interaction. For example, if the penetration proceeds only through the first k elements of a n-element armor array ($k < n$), the ballistic test evaluates only the first section of the armor ($1 \le i \le k$), and the armor performance measures for that particular section can be derived. However, in order to evaluate the measures for the complete n-element armor, the appropriate thickness equivalences (e_k through e_n) must be known. Without this additional information, the original objective of the ballistic test--to evaluate the performance measures of the complete n-element armor array--cannot be achieved.

2.3 Homogeneous or quasi-homogeneous armors

Some armors either are strictly homogeneous, or, they respond like homogeneous armors. In broad terms, they are characterized by an incremental response to penetration that is independent of the

location within the armor. This implies a constant RHA thickness equivalence and density for each increment of the armor thickness. An overmatched ballistic test resulting in positive residual penetration, R_o, into the RHA witness pack is of course evaluated as before by using equations (8). The undermatched case is evaluated by using again the concept of equivalent RHA thickness.

$$T_o \equiv E_s(T-|R|),$$

$$\rho_o T_o \equiv E_m \rho(T-|R|),$$

where $|R|$ is the absolute value of the perforation margin (not in RHA but in the quasi-homogeneous armor) measured from the back face of the target. Note that again $E_s/E_m = \rho/\rho_o$, independent of the ballistic test result. Using the earlier sign convention (perforation margins are negative residuals), the effectiveness factors are given by:

$$E_s = T_o/(T+R), \text{ and}$$

$$E_m = \rho_o T_o/\rho(T+R). \tag{9}$$

With the known ratio of E_s and E_m this can be rearranged as:

$$E_s = (T_o-E_sR)/T,$$

$$E_m = (\rho_o T_o-\rho_o E_s R)/\rho T. \tag{10}$$

The term E_sR constitutes simply a conversion of the measured residual penetration in the armor, to an equivalent residual penetration in RHA, ie, $E_sR = R_o$. This is justified by the assumptions made for this particular, homogeneous or quasi-homogeneous, armor.

2.4 General Case

Equations (8), (9), and (10) may be combined as:

$$E_s = \frac{T_o}{T+R} = \frac{T_o-R_o}{T},$$

$$E_m = \frac{\rho_o T_o}{\rho T+\rho R} = \frac{\rho_o T_o-\rho_o R_o}{\rho T} = E_s/r^2$$

$$r^2 = \rho/\rho_o, \tag{11}$$

$$Q = E_s/r,$$

$$\rho_e = \rho Q,$$

which apply in all cases. The part of the expressions containing R is applicable only to homogeneous or quasi-homogeneous targets for the undermatched test case (R<0). R_o is the positive or negative residual penetration in RHA.

3 SUMMARY AND RECOMMENDATIONS

Simple performance measures of the kind discussed above are useful provided sufficient information about the details of the armors and penetrators are available. Effectiveness factors like E_s and E_m, or armor quality measures like Q, are simple, descriptive measures representing the performance of an armor against one particular penetrator. The actual values are highly dependent on the specific details of usually complex penetrator-target interactions. One additional problem not specifically addressed here is the dependence of the performance measures on armor obliquity. The implicit assumptions are that armors are evaluated only at the obliquity of a particular design. Most complex armors do not conform with the simple line-of-sight thickness relation, ie, their performance increases or decreases by different amounts than expected from the increase or decrease of line-of-sight thickness alone.

In order to determine the effectiveness measures, a ballistic evaluation of the armor-penetrator combinations is required. The preferable method is to attempt a perforation and to measure the additional residual penetration in an RHA witness pack behind the armor. It is advisable to keep the residual penetrations (overmatch of the armor by the penetrator) as small as practical. In the case of undermatch, where the armor is not perforated, the same methodology can be applied to determine the effectiveness measures, provided the elements of the armor not affected by the penetration process are readily represented in terms of equivalent RHA. Again, it is advisable to keep the mismatch between the penetrator and the armor as low as practical. Severe mismatching usually leads to systematic variations of the effectiveness measures.

The simple armor effectiveness measures, like E_s, E_m, Q, etc., attempt to represent the performance of complex armors by one single number, the equivalent RHA thickness. In fact, the ballistic tests required to determine the effectiveness numbers are direct comparisons between complex armors and RHA targets. A single number like the equivalent RHA thickness cannot be expected to represent the result of generally very complicated penetrator-target interactions in a unique, universally applicable fashion. However, if properly evaluated, the effectiveness measures serve well to assess and catalog the relative merits of armor materials, armor elements, armor technologies, and armor defeating hardware. If properly applied, they become convenient and useful tools for the initial design of armor-anti-armor components, for evaluating possible trade-offs, and for complete system studies.

LIST OF SYMBOLS AND ABBREVIATIONS

KE - kinetic energy

CE - chemical energy

E_s - space effectiveness factor

E_m - mass effectiveness factor

e - thickness equivalence (RHA)

e_i - thickness equivalence (RHA) of the armor element i

R - residual penetration

R_o - residual penetration in RHA

Q - armor quality factor

$r^2 = \rho/\rho_o$ - relative density of armor (RHA)

RHA - rolled homogeneous armor, armor steel used for reference

T - thickness of armor (line-of-sight)

T_n - thickness of the armor element n (line-of-sight)

T_o - thickness of RHA perforated/penetrated by the reference penetrator (limit thickness)

$\varepsilon_s = 1/E_s$ - relative thickness (RHA)

$\varepsilon_m = 1/E_m$ - relative areal mass (RHA)

ρ - density of the armor

$\rho_e = \rho Q^2$ - apparent or effective density of the armor

ρ_n - density of the armor element n

ρ_o - density of RHA (7850 kg/m^3)

APPENDIX A

PENETRATION-PERFORATION OF STEEL TARGETS (RHA)

The characteristic differences between penetration and perforation of steel are illustrated in Figure A-1. With a sufficiently thick RHA target (ideally a semi-infinite target) the test penetrator (KE rod or shaped charge jet) generates a penetration channel of depth P_o, as shown. The same test penetrator is capable of just perforating a finite thickness RHA target of thickness T_o. The difference between P_o and T_o is typically of the order of 1 to 2 penetrator diameters in the direction normal to the target and is caused by the break-out phenomenon on the free rear surface of the finite target.

The exact details of the breakout and the difference between P_o and T_o are highly dependent on details such as plug formation, bluge development, penetrator length or mass remaining just before the penetration proceeds to within the rear surface, and other usually unknown factors. In the case of shaped charge penetrators the differences are usually negligible. A typical shaped charge jet penetrates more than about 100 jet diameters so that the differences are usally of the order of 1% or less.

With KE penetrator the difference may become appreciable. A typical long rod penetrator is capable of penetrating about its length of RHA. With L/D ratios of 10 to 20 the differences between P_o and T_o become of the order of 10% which can not be neglected. In addition, the break-out effects cause a systematic obliquity dependence of the line-of-sight thickness, T_o, that can be perforated by a KE penetrator. In general, an efficient long rod penetrator can "just" perforate between 10% to 40% more line-of-sight thickness at higher obliquities (60^o or more) than at obliquities of around zero degrees. This needs to be considered in the evaluation of performance measures of armors.

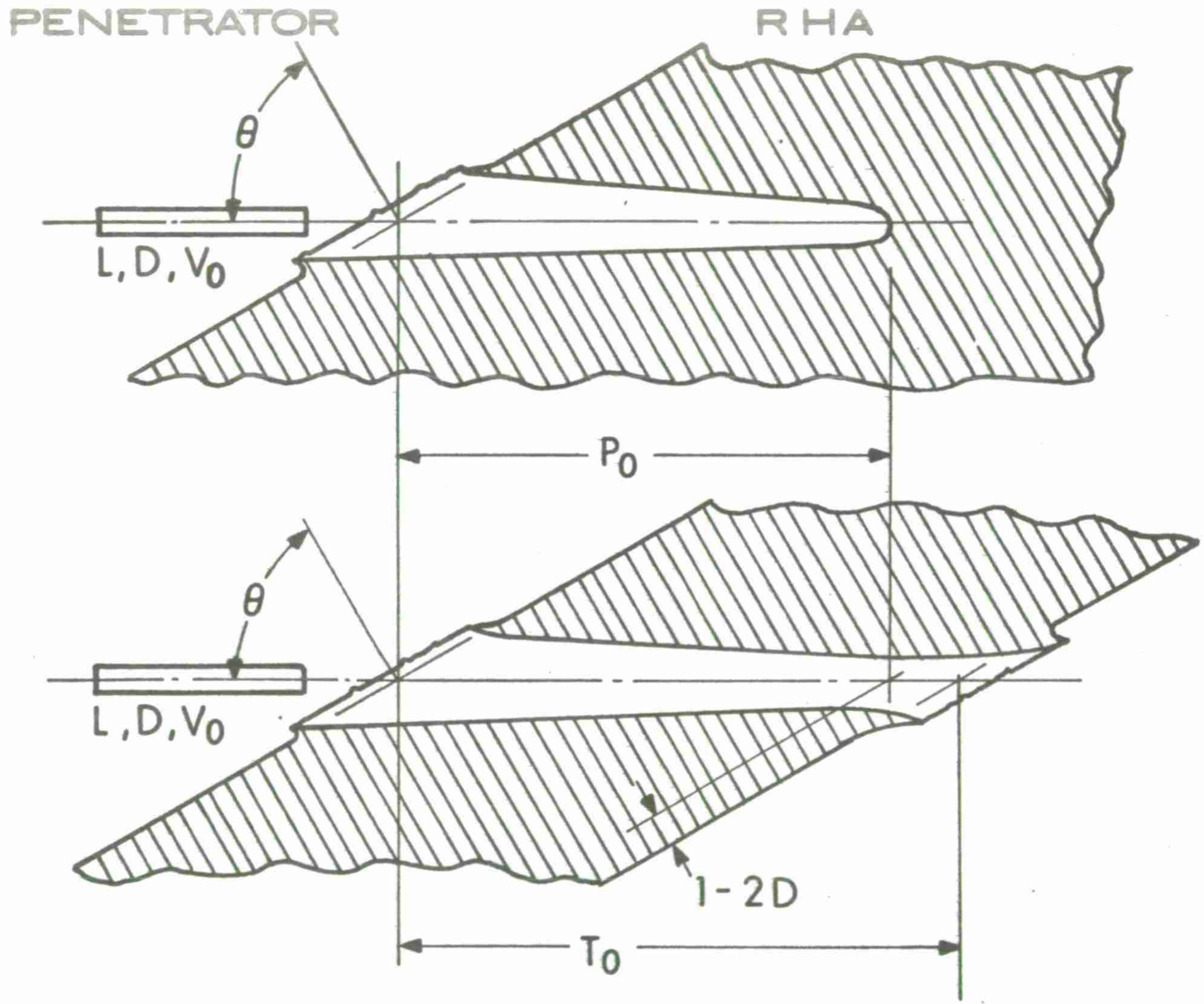

Figure A-1. Illustration of the difference between penetration capability P_o and perforation limit thickness T_o

APPENDIX B

RESIDUAL PENETRATIONS AND RHA WITNESS PANELS

The current practice of evaluating armors is illustrated in Figure B-1. A stack of RHA plates of sufficient thickness is placed parallel to the rear surface of the target, separated by an air space, S. The purpose of the air space is to decouple the witness stack from the armor in order not to interfere with the perforation and breakout process. The residual penetration, R_o, is measured as indicated. The air space, S, needs to be specified, but it is not considered in the evaluation of the armor performance measures.

In general, a ballistic test that perforates the armor is preferrable. The weapons designer needs data on the behind armor capability of his penetrator (lethality) and he obtains those data to first order from the residual penetration, R_o, or, if need be by more refined techniques. The armor designer, on the other hand, is generally reluctant to demonstrate armors that are perforated. However, a perforation with an assessment and quantification of the residual penetrator capability seems to be the only way to assess the performance limits of the armor. Nonperforating ballistic test resulting in negative residual penetrations are of limited value because of the nonlinear response due to the break-out effects (Appendix A). The approximation, $E_s T + R_o = T_o$, used for miss-matched ballistic tests ignores break-out effects completely, and, in addition, constitutes a linearized approximation to a nonlinear response, both for positive ($R_o > \phi$) and negative (R or $R_o < \phi$) residuals.

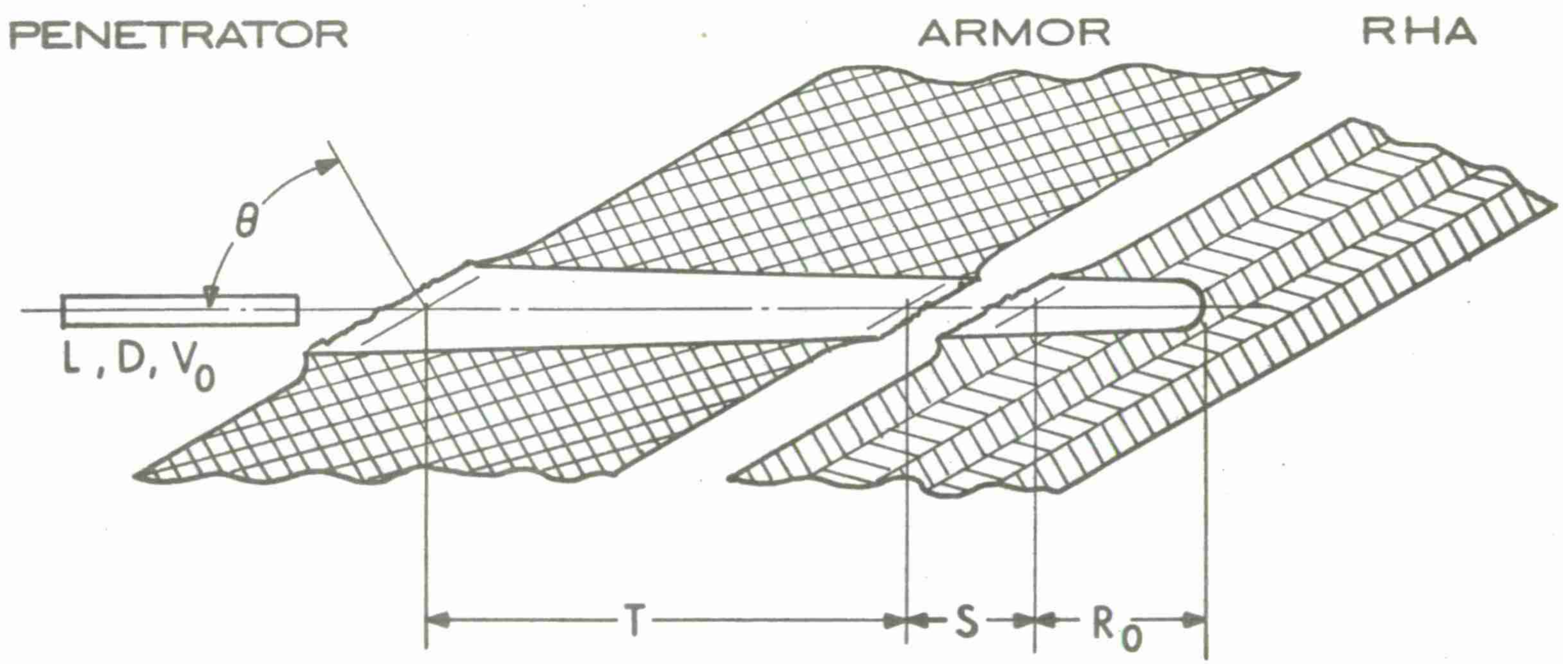

Figure B-1. Experimental determination of the residual penetration R_o by RHA witness plates

APPENDIX C

SUCCINCT SUMMARY OF DEFINITIONS,

PERFORMANCE MEASURES AND

BALLISTIC EVALUTAION PROCEDURES

1. The penetration/perforation limit in monolithic RHA is used for reference. The penetrator is capable of penetrating to a distance of P_o into RHA, or just perforating a finite thickness T_o of RHA. The relation between P_o and T_o is addressed in Appendix A. The preferred reference numbers are:

$$\rho_o, T_o$$

2. The performance of an armor, characterized by the average density ρ and the overall thickness T, that just defeats the same penetrator can be described by the following interdependent, non-dimensional performance measures:

a. Space Effectiveness $\qquad E_s T = T_o$

b. Mass Effectiveness $\qquad E_m \rho T = \rho_o T_o$

c. Thickness Equivalence, when applied to the individual armor elements

$$e_1 T_1 + e_2 T_2 + \ldots + e_n T_n = T_o$$

$$(T, + T_2 + \ldots\ldots + T_n = T)$$

d. Relative Thickness $\qquad T = \varepsilon_s T_o$

e. Relative Mass $\qquad \rho T = \varepsilon_m \rho_o T_o$

f. Armor Quality Factor $\qquad Q^2 = E_s E_m$

3. The above definitions imply a matched ballistic test, i.e., armor or penetrator "just defeated". A mismatched ballistic test result is approximated by

$$E_s T + R_o = T_o,$$

where R_o is the residual penetration in RHA as defined in Appendix B. Together with the known relative density of the armor, $r^2 = \rho/\rho_o$, the performance measures are derived from the ballistic test results by using

$$E_s = (T_o - R_o) / T$$

$$E_m = E_s / r^2$$

The pairs E_s and E_m, or the alternate pairs Q^2 and r^2, may be used with some precautions, as indicators of the performance of a particular armor technology against a particular class of armor penetrators.

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